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# Gearless generator with magnets on the stator for wind turbine

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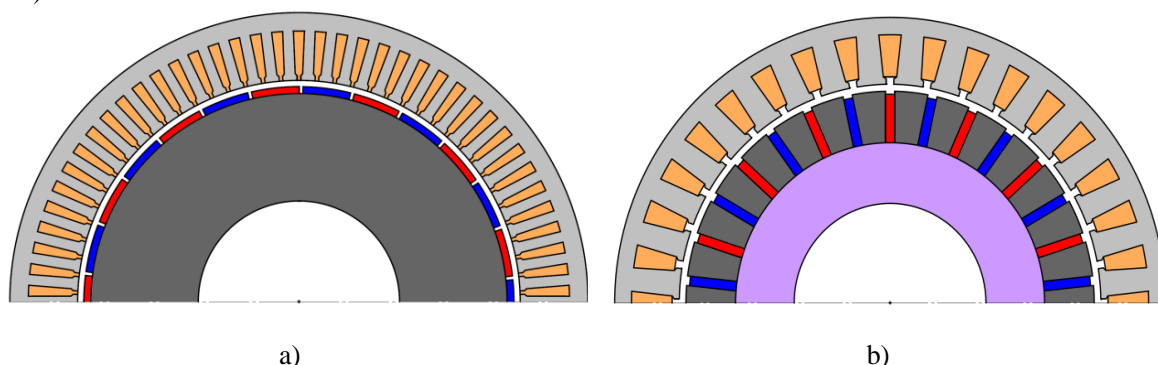
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**Abstract.** In this work a new design of multi-pole gearless low-speed Generator with Magnets on the Stator (GMS) for wind turbine is described. Gearless GMS combines both high number of magnetic poles created by magnets and low-pole winding creating strong electromotive force. Therefore GMS has high efficiency and low operational speed. The GMS mathematical model has been developed. The low-speed gearless GMS was designed with the help of the developed mathematical model. Comparison of the designed GMS with a generator with magnets on the rotor (SG) is given. The GMS active material cost is 2.3 times less than that for the SG. The GMS mass is 1.3 times less. The GMS has higher efficiency at the rated speed. Also GMS maintain high efficiency in wide range of torques and speeds and GMS torque ripple is low.

## 1. Introduction

Multi-pole synchronous generators with magnets on the rotor (SG) are commonly used in gearless wind turbine generators. However, making such SG of small outer diameter is not easy. For example, the gearless SG (350 rpm, 3141 W, 228 mm of outer diameter, model 300STK2M) with distributed winding has 24 poles on its rotor and 72 teeth on the stator (the slot number per pole and phase is  $q = 1$ ) [1] (Figure 1a). Further increasing the number of the poles is difficult because it leads to increasing number of the stator teeth, decreasing the copper fill factor and, as a result, decreasing the efficiency.

A SG with concentrated winding can have a little higher number of poles than a SG with distributed winding. For example, gearless SG (200 rpm, 3000 W, 280 mm of outer diameter) has 30 poles on the rotor and 36 teeth on the stator (the slot number per pole and phase is  $q = 0.4$ ) [2] (Figure 1b).



**Figure 1.** a) SG design according to [1]; b) SG design according to [2].

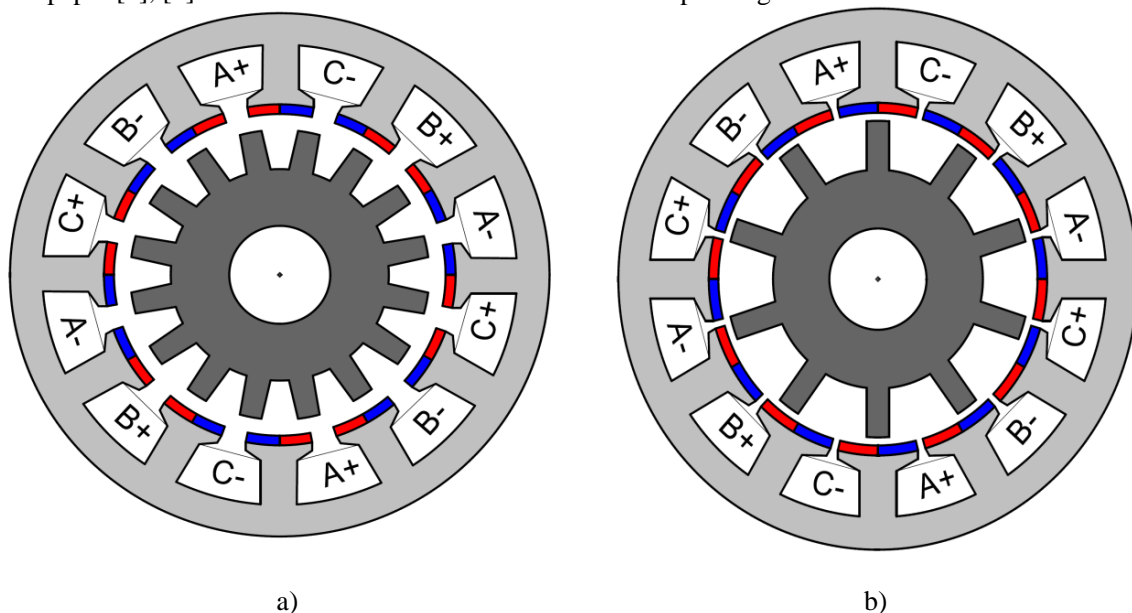
However, significant drawbacks of the SG with concentrated winding and small fractional number  $q$  of the slots per pole and phase are high torque ripple and nonsinusoidal magnetomotive force (MMF) distribution in air gap which worsens the generator efficiency, specific power and torque.

These two SGs are commonly used solutions for wind generators and characterized in lessening the pole pitch when the number of poles increases. As a result, the winding MMF at the same current density decreases compared to that of the SG with lower number of poles which leads to decreasing the generator efficiency.

Generators with magnets on the stator (GMS) can be designed on the basis of Flux Reversal Machines (FRM). The first FRM was described in [3]. FRMs can be used as low-speed motors and generators because of easiness of increasing number of poles, even in small diameter of stator and without losing MMF. For example, the energy-efficient multi-pole single-phase FRM is described in [4]. Magnets on the FRM stator teeth create large number of poles (32 poles) in the small stator diameter (100 mm). The FRM stator winding is concentrated and has just 4 poles. Using the winding with small number of poles increases its MMF with the same current density. Therefore, the winding losses are decreased significantly which increases the efficiency. The comparison of the 32-pole FRM with the outer stator core diameter of 100 mm to the 16-pole synchronous machine with magnets in the rotor and with the outer stator core diameter of 110 mm is given in [4]. The FRM efficiency is much higher than that of the 16-pole synchronous machine with magnets in the rotor. However, single-phase machines such as in [3], [4] have large cogging torque and torque ripple and cannot be used in wind generators.

A vast overview of various three-phase FRM designs with magnets on the stator teeth is given in [5]. However, the windings of these machines are concentrated and with small pole pitch which results in decreasing the winding MMF, the efficiency and specific power. Also, those FRM have large stator slot openings creating a dip in magnetic field, decreasing the efficiency and the specific characteristics and increasing torque ripple. Hence, these machines are not widely used.

Multi-pole three-phase FRM with distributed winding (Figure 2a) is described in [6]. Authors of both paper [5], [6] note that FRM suits for direct driven wind power generation.



**Figure 2.** a) FRM design according to [6]  $z = 12, r = 16, q = 1, p = 2, m = 24$ ;  
b) New FRM design  $z = 12, r = 10, q = 1, p = 2, m = 24$ .

The multi-pole FRM from [6] with the distributed winding contains (see Figure 2a):

- Stator with a twelve-tooth magnetic core and a distributed winding with four poles, where the number of pole pairs of the stator winding  $p$  is 2, and the number of poles per pole and phase  $q$  is 1.
- Each tooth of the stator has two magnets of equal size, the adjacent magnets located on one and the same stator tooth are magnetized in the opposite direction.
- The stator has open slots, which openings are approximately equal to the width of the magnet.

- Neighboring magnets located on adjacent stator teeth are magnetized identically.

In this machine, the number of teeth of the stator is 12, the number of magnets on the stator is 24, and the number of teeth of the rotor is 16, the surface of the stator teeth occupies about 2/3 (66.7%) of the inner stator surface, and 1/3 (33.3%) of the inner stator surface is not used (slots openings).

The disadvantages of this design are:

- Efficiency and specific power are not very high, because 1/3 (33.3%) of the stator surface is not used.
- Complex harmonic composition of the magnetomotive force (MMF) of the magnets due to a violation of the periodicity of their alternation by the large slot openings and the presence of additional undesirable harmonics in the MMF. Because of this, there are large torque ripple and cogging torque, acoustic noise and vibrations.

All FRMs considered in [5], [6], [7], [8] have a similar operating principle, the same faults (large moment pulsations and not very high efficiency) and are not widely used in practice.

## 2. Proposed new FRM design

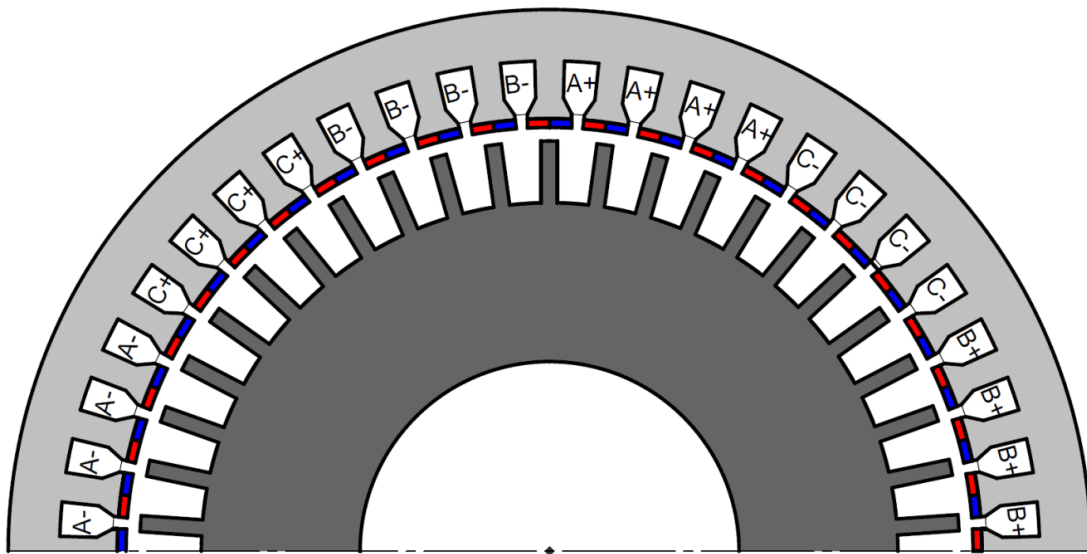
A new FRM design with distributed winding and with small stator slot openings was described in the little-known paper [9]. However, multi-pole three-phase gearless machines based on that FRM design was not investigated in detail. In this paper, such design of the new multi-pole gearless FRM is proposed as a generator for wind turbines. Figure 2b demonstrates the simplest embodiment of such FRM design, which contains:

- Stator with a twelve-teeth magnetic core and a distributed winding with four poles, where the number of pole pairs of the stator winding  $p$  is 2, and the number of poles per pole and phase  $q$  is 1.
- Each tooth of the stator has two magnets of equal size, adjacent magnets are magnetized in the opposite direction.
- There are closed slots between the stator teeth, the opening of which are very small.
- Neighboring magnets located on adjacent stator teeth are magnetized in the opposite direction.

In the FRM shown in Figure 2b, the total number of teeth on the stator is 12, the number of magnets on the stator is 24, and the number of teeth of the rotor is 10, the slot opening is very small and depends on the thickness of the winding wire. Therefore, the surface of the stator teeth occupies almost the entire inner stator surface (almost 100%). In the FRM shown in Figure 2b, torque ripple, cogging torque, acoustic noise, vibrations, moment of inertia of the rotor is lower, and the specific power and efficiency of the electric machine is higher compared to that in the conventional FRM.

The number of teeth on the stator, the number of magnetic poles on the stator surface in the FRM with the distributed winding can be easily enhanced by increasing the number of slots per pole and phase  $q$ , which is especially important for gearless applications. According to the recommendation in [9], for each pair of the stator winding poles the number of rotor teeth is greater or less than the number of the magnets magnetized in the same direction by one. Namely, the number of rotor poles can be calculated as  $r = m / 2 \pm p$ . For example, in the FRM shown in Figure 3, the total number of teeth on the stator is  $z = 48$ , the number of magnets on the stator is  $m = 96$ ,  $q = 4$ , the number of pole pairs of the stator winding is  $p = 2$ . The number of rotor teeth is  $r = 96/2 - 2 = 46$ . The FRM (Figure 3) has distributed four-pole winding which allows obtaining high MMF at small current density which significantly decreases the winding losses and increases the efficiency of the FRM.

The electric frequency of the FRM generator is  $f = r \cdot n / 60$  (measured in Hz), where  $n$  is the rotor speed measured in rpm.



**Figure 3.** The proposed new FRM design with  $z = 48$ ,  $r = 46$ ,  $q = 4$ ,  $2p = 4$ ,  $m = 96$ .

In order to design and study the characteristics of FRM, the mathematical model based on the finite element method (FEM) has been developed.

### 3. Mathematical model description

Various approaches to the mathematical modeling of the single-phase FRM are given in [4], [10]. Those models are developed for supply by voltage of rectangular form. In this paper, sinusoidal form of supply currents is assumed for three-phase FRM. Such approach is widely used for simulating other three-phase motors and generators fed with frequency converters. The model is based on solving a set of 2D magnetostatic problems. Usual gauge fixing  $A_x = A_y = 0$  is used for vector potential:

$$B_x = \frac{\partial A_z}{\partial y}, B_y = \frac{\partial A_z}{\partial x}, \quad (1)$$

$$\iint (\mathbf{H} \delta \mathbf{B} - J_z \delta A_z) dx dy = 0, J_z = \sum_k \Xi_k I_k,$$

where  $\mathbf{H}$  and  $\mathbf{B}$  are in-plane magnetic field and flux density.  $J_z$  is perpendicular to the plane component of the current density. Other components are equal to zero:  $J_x = J_y = 0$ .  $I_k$  is the current of the  $k$ -th phase,  $k = A, B, C$ ;  $\Xi_k(x, y)$  are the current density fields when only the  $k$ -th current  $I_k$  is nonzero and equal to 1 A.  $\Xi_k(x, y)$  can be nonzero only in the stator slot areas.

In general case a set of magnetostatic boundary problems should be solved for various rotor positions. One and the same calculation area is used for all boundary problems. For doing so, the entire calculation area is divided into two parts. One part contains the rotor and the half of the air gap. Another part contains the stator and another half of the air gap. These two parts are joined with a boundary condition depending on the rotor position. As a result, rotor and stator are considered in their own reference system.

Due to the generator symmetry, the calculation area can be halved (Figure 3). Periodic condition is applied on the emerged boundary. Also, only rotor position interval of sixth of electrical period that is of  $360 / 46 / 6 = 1.3$  degrees should be taken into consideration.

The generator power, losses in the winding, in the steel and in the magnets, the efficiency, and the torque ripple and so on are calculated in post-processing.

Winding losses can be easily calculated using the Joule–Lenz law. The estimation of losses in stator and rotor cores is more complicated and is done in postprocessing.

During the calculation of the core losses it should be taken into consideration that the magnetic flux is not sinusoidal. So the harmonics contribution should be evaluated.

Averaged magnetic losses density in steel is supposed to be given by the expression:

$$p_{st} = \frac{\alpha}{\omega^2} \left\langle \left( \frac{d\mathbf{B}}{dt} \right)^2 \right\rangle = \frac{\alpha B_{equ}^2}{2}, \quad (2)$$

where  $\alpha$  is the proportionality factor determined on the basis of empirical data,  $\omega = 2\pi f$  is the angular frequency of the supply,  $\langle \rangle$  is averaging over the interval of rotor position for which the boundary problems are solved,  $f$  is frequency and the equivalent flux density is

$$B_{equ} = \sqrt{2 \left\langle \left( \frac{d\mathbf{B}}{d\varphi_e} \right)^2 \right\rangle} \quad (3)$$

The total derivative of  $\mathbf{B}$  shows the change  $\mathbf{B}$ , at the same point of the medium (steel cores) with changing the rotor position (electric) angle  $\varphi_e$ .

Having  $B_{equ}$ , the C. Steinmetz expression was assumed for calculating the losses density:

$$p_{st} = \rho \cdot p_{50} (f / 50)^s B_{equ}^2 \quad (4)$$

where  $\rho$  is the steel density,  $p_{50}$  is losses in 1 kg of steel at 50 Hz and 1 T;  $s$  is the parameter which is taken as  $s = 1.3$  for the majority of electrical steels.

The stator and rotor core losses can be found with integrating the expression (4).

Although coefficient in (4) is calculated using the steel datasheet data, the expression for  $\alpha$  taking into consideration the steel eddy current losses is also known:

$$\alpha = \frac{\omega^2 \sigma \chi^2}{12}, \quad (5)$$

where  $\sigma$  is electric conductivity of considered material (steel),  $\chi$  is a lamination thickness, that is a thickness of the material pieces in the direction perpendicular to the magnetic flux.

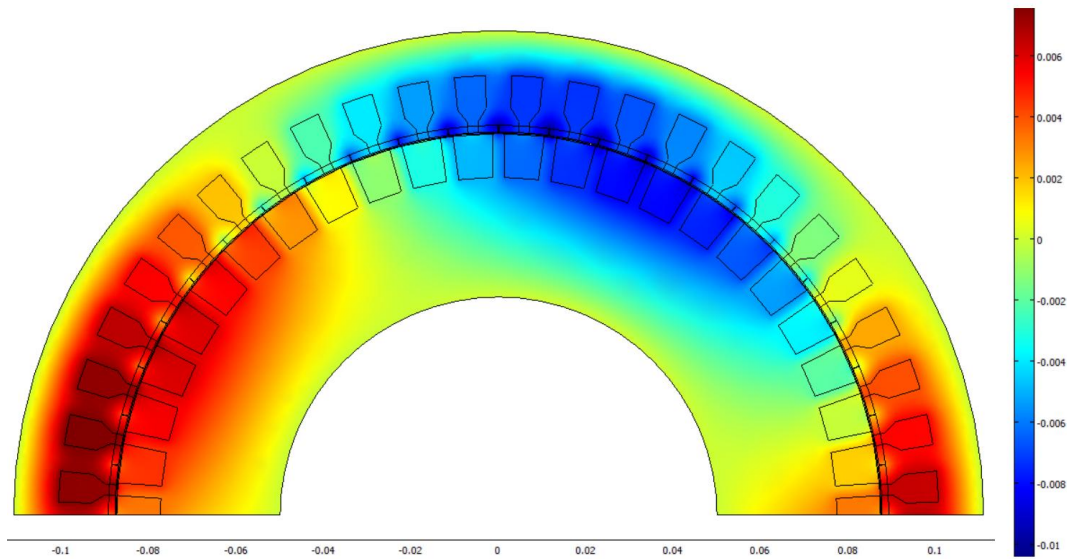
The equation (5) was used for estimating the losses in the magnets. The conductivity of the magnets is assumed to be 700 kS/m. The magnet arc length is taken for  $\chi$ .

Formula (5) is derived from the assumption of uniformity of the magnetic flux density field. This is a good assumption for thin laminated steel. The magnetic field density can differ significantly along the magnet arc. However the calculations show that the magnet losses are not very high and cannot influence significantly on the FRM efficiency and its performance. Hence, accurate calculations of the eddy current losses in the magnets are not required.

#### 4. Example of FRM design for wind generator

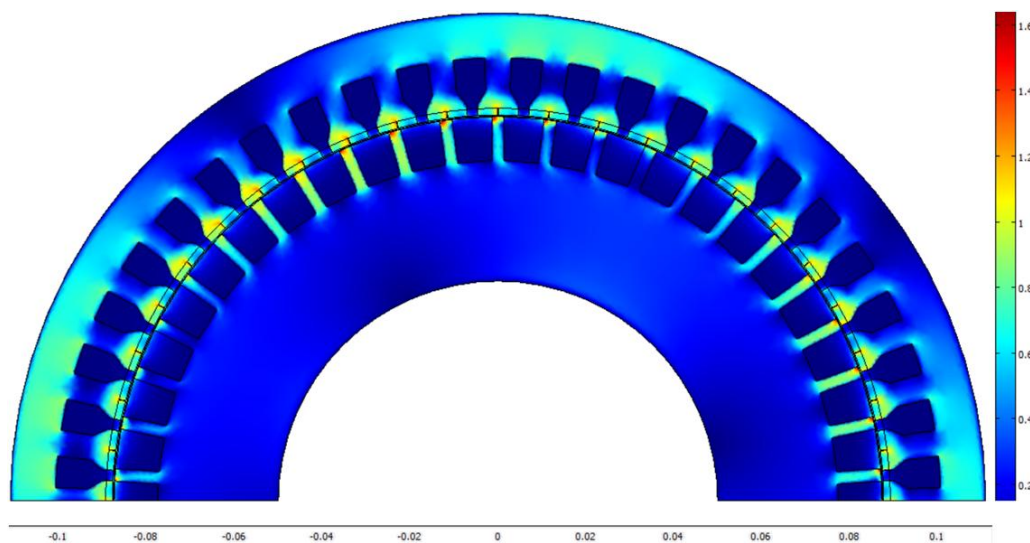
3 kW, 200 rpm FRM was designed on the basis of the developed mathematical model. The calculations are done for the laminates steel of M250-50A grade and for the rare-earth magnets which remanent flux density is 1.1 T and coercivity with respect to magnetization is 750 kA/m. The FRM geometry and vector potential field are shown in Figure 4. This figure demonstrates the emergence of the four-pole magnetic field. Also it can be seen that vector magnetic potential is not continuous and that of the stator is shifted with respect to that of the rotor which demonstrates the boundary condition joining both parts of calculation area.





**Figure 4.** Geometry FRM and vector potential field (Wb/m).

Figure 5 demonstrates the flux density in FRM. In the most parts of the machine flux density does not exceeds 1T.



**Figure 5.** Geometry FRM and flux density (T).

The FRM calculation results were compared to the calculation results of synchronous generator (SG) with magnets on the rotor [2]. The FRM and SG parameters are shown in Table 1. Since the number of poles of the FRM is greater than of the SG, the electric frequency of the FRM at the same speed is about thrice as high.

Compared to the SG, the FRM stator core length is increased and the FRM stator core diameter is decreased that is the FRM takes the shape specific to the low-pole machines because of a small number of the winding poles.

Table 1 shows significant advantages of the FRM over the SG. The efficiency of the FRM is 2.3% higher than of the SG which corresponds to 32 % reduction of the losses. The FRM cooling is simpler and it can run at higher ambient temperature. The core volume that is  $V = \pi D^2 L / 4$  (where  $D$  is the outer stator core diameter and  $L$  is the stator core stack length) is reduced by 25.6%.

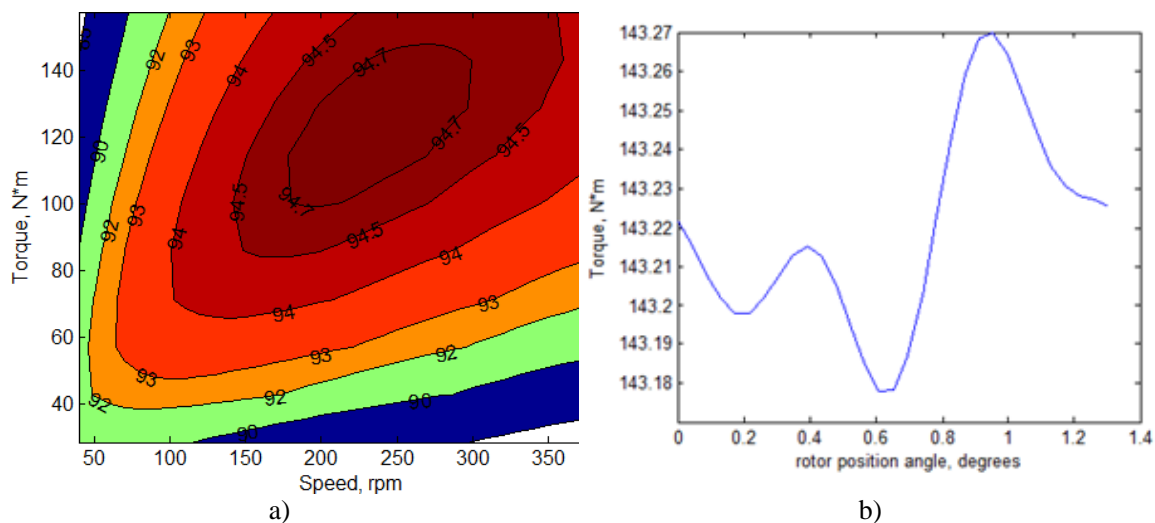
Active materials costs also were calculated. The reference prices that were assumed for this calculation are: 50 Euro/kg for PMs, 7.5 Euro/kg for copper and 3 Euro/kg for stator and rotor steel [2].

The table 1 shows that the mass of the expensive rare-earth magnet required for the GMS is 5 times less than that of the SG. The active material cost is reduced by 2.3 times. The active material mass is reduced by 1.3 times.

**Table 1.** Parameters of 3kW 200 rpm gearless generators.

Parameters	FRM	SG [2]
Rated power, kW	3	3
Rated speed, rpm	200	200
Rated efficiency, %	94.6	92.3
Rated frequency, Hz	153	50
Winding type	distributed	concentrated
Number of winding poles, $p$	4	30
Number of stator teeth per pole and per phase, $q$	4	0.4
Number of stator teeth	48	36
Number of poles created by permanent magnets	96	30
Magnet type	rare-earth	rare-earth
Remanence of magnets, T	1.2	1.2
Stator outer core diameter ( $D$ ), mm	222	280
Stack length of stator core ( $L$ ), mm	237	200
Core volume ( $V$ ), litres	2.9	3.9
Copper mass, kg	5.3	9.1
Stator and Rotor Steel mass, kg	38.6	44.7
Magnet mass, kg	1.0	5.6
Total active material mass, kg	45.0	59.4
Active materials estimated cost, Euro	206	480

The FRM efficiency map is shown in the Figure 6a. The FRM has high efficiency in wide range of torques and speeds.



**Figure 6.** a) FRM efficiency map; b) FRM torque ripple.

Figure 6b shows the torque ripple at the rated load. The peak to peak value of the torque ripple is less than 0.1 % of the torque mean value. The torque ripple is extremely small although it was not even chosen as optimization parameter.



Since the 3kW SG was taken for the comparison, the 3kW GMS (FRM) was designed. Generators with higher rated power will have higher dimensions which make it possible to increase the number of poles. Therefore, a greater increase of the FRM rated power density compared to that of a traditional SG is expected in this case. This question requires more detailed investigations and will be considered in future work.

## 5. Conclusions

The paper describes a new GMS (Flux Reversal Machine) design developed for wind turbine application.

The main advantages of the gearless low-speed GMS compared to SG: 1) Making low-speed multi-pole generator with 80 poles on the stator and more in small diameter is easy; 2) Mass of the expensive rare-earth magnets is 5 times less than that in analogues with magnets on the rotor; 3) The toothed rotor is simple and reliable because its active part is made only of the laminated steel; 4) The active material cost twice as low as that of the analogue with magnets on the rotor; 5) The GMS has higher efficiency than analogues; 6) The torque ripple is extremely small although it was not even chosen as optimization parameter.

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